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**Center for Space Telemetry
and Telecommunication
Final Report**

June 1, 1989 through May 30, 1991

NAGW 1746

For

**NASA
Office of Space Operations
Associate Administrator
For Space Operation
NASA Headquarters
Washington, D.C. 20546**

**Submitted by Frank Carden
Center Director
Electrical Engineering Department
New Mexico State University**

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TELEMETERING AND TELECOMMUNICATION
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SECTION 1

OVERVIEW

The mission of the Center for Space Telemetry and Telecommunications Systems (STTS) located at NMSU is helping NASA fulfill its goal of exploring the solar system.

Specific research goals were

- 1) continue basic research in the study of advanced communication systems for near-earth-orbit application,
- 2) research in telemetry systems including the transport technology and techniques for data analysis,
- 3) laser communication.

Specific projects are underway in order to implement these goals.

The faculty staffing of the Center is complete and the graduate students necessary for the research projects have been recruited and are on board. However, recruiting outstanding graduate students will remain an important ongoing activity.

SECTION 2

**CENTER FOR
SPACE TELEMETERING AND
TELECOMMUNICATION
SYSTEMS**

Introduction

New Mexico State University and the National Aeronautics and Space Administration have established a Center for Space Telemetering and Telecommunications Systems (STTS) at NMSU. The Center is aimed at helping the space community fulfill the long-range goals outlined in "Pioneering the Space Frontier", the report of the National Commission on Space and "Leadership and America's Future in Space", by Dr. Sally K. Ride. Two of the fundamental technologies mentioned by the National Commission on Space to support access to the solar system, which are (1) advances in earth-observation sensors and data analysis and (2) new communications techniques suitable for deep atmospheric probe missions, can be directly supported through the activities of this Center. This same report also identified the need to develop the necessary communications infrastructure to support the command and control structure required for exploration of the solar system, including lunar and martian bases. Research in these areas is also relevant to the activities of the Center. In Dr. Ride's report, exploration of the solar system, a lunar outpost, and an eventual martian base are identified as potential NASA missions. The research activities of the Center are directed toward playing an important role in the development of the necessary technology to support these activities.

During the period of the grant and within the general NASA goals stated above, the STTS center at NMSU performed research in telecommunication in the following necessary areas for advancing the nation's efforts in space.

Task 1 basic research in the study of advanced communication systems, primarily in near-earth-orbit applications;

Task 2 research begun in telemetry systems including the transport technology and techniques for data analysis, and

Task 3 advanced optical communication technology.

The results from the research program was made available to the engineering community via the departmental educational program and normal publication means.

Substantial activity supporting this grant was initiated at the start of the Fall 1989 semester. A major effort was made to attract, recruit and retain outstanding graduate students. This was a successful effort in that we now have 12 MS and six doctoral students working on projects for the grant. Major research programs were initiated.

A visit was made to JSC to discuss research areas of mutual interest in the communication systems area with the Tracking and Communication and the Systems Development divisions. Goddard Space Flight Center was also visited to discuss research areas with the Instrument and the Information Processing Divisions.

The STTS center has helped NMSU achieve a higher quality of interaction with NASA headquarters and field centers. In particular, the center being located at NMSU lead to Dr. Stephen Horan being invited by Johnson Space Center to participate with them in developing inputs for the Space Transportation Avionics Technology Symposium held in November 1989. The STTS center was also part of the demonstrated excellence in sponsored research for which NASA headquarters was seeking when they designated NMSU as one of the Space Grant institutions in December 1989. This center has also improved interactions with Goddard Space Flight Center and Johnson Space Center and the Jet Propulsion Laboratory, as well as non-NASA members of the aerospace and telemetering community.

Three specific research areas were expanded under the research goals and are outlined in the paragraphs below.

Advanced Communication Systems.

1. The primary thrust of the research was directed towards the study of advanced communication systems for near-earth-orbit. Overall, the research was involved in end-to-end system concepts and in the study, analysis, simulation and proof-of-concept implementations of these types of advanced communication systems. Systems employing nearly-constant envelopes, necessary in satellite communications, and that are efficient both in terms of bits-per-second of information transmitted per hertz of bandwidth and in terms of symbol error rate for a given signal-to-noise ratio, were being studied in depth. Spectrally-efficient modulation schemes such as minimum shift keying, m-ary phase shift keying, and m-ary orthogonal signaling are being integrated into communication systems and the system performance

studied. Various coding schemes are being studied such as new techniques employing combined coding and modulation such as trellis coded modulation and multi-h continuous phase modulation. Video compression and enhancement techniques are being developed and evaluated with respect to space communication systems.

A strong emphasis was placed on the simulation of advanced communication systems employing higher level modulation techniques. This is a cost effective method of determining performance in terms of system parameters. This is especially true for M-ary systems utilizing combined modulation and coding techniques since the hardware necessary to implement the system is not available in an off-the-shelf mode. After extensive computer simulations, however, hardware implementation of advanced communication system concepts was initiated in order to validate proof of concept.

2. Research in telemetry transport technology was based on current research in parallel processing and packet data standards being conducted for the space station. This research was expanded to investigate new issues which are arising from the current contract as well as begin looking at the data transport infrastructure which was required to unite ground station, space station, lunar bases, and transport vehicle. This research used computer-based simulation to model the links and transport methods to attain performance estimates and to understand the workings of the protocols used for data transport.

3. Research in optical communication implemented and evaluated optical filters.

The Computer Assisted Design and Simulation Laboratory (CADSL), the Communication Research Laboratory and the Laser Communication Laboratory were developed as part of this grant.

SECTION 3
RESEARCH PROGRAMS
Section 3-1

1. ADVANCED COMMUNICATION SYSTEMS
TASK 1

Introduction

Communication systems employing coding schemes that enhance bandwidth efficiency by combining modulation and coding such as Trellis Coded Modulation, TCM, and multi-h continuous phase modulation were studied.

The overall approach proposed was to create concepts, develop supporting mathematical models for analysis, then go to the CADSL for extensive simulations.

Trellis Coded Modulation

M-ary TCM demodulation and trellis soft-decision decoding, in contrast to binary signaling and Hamming distance calculations, requires two dimensional Euclidean operations which increase the complexity of the decoder, the decoding task and the processing time. To date, the major emphasis in this work has been on the creation, study, analysis and simulation of fast TCM Euclidean decoders for 8-PSK using short memory codes. Mathematical and simulation models of circularly quantized Euclidean decoders, QED, [Carden, 1, 2, 3, 4] were developed. The QED reduces the trellis metric Euclidean calculation to a table look-up procedure creating a faster, less complex and easier to implement decoder. However, the metrics used by the QED in decoding are suboptimal compared to the maximum likelihood decoding of the decoder using actual calculated Euclidean distances.

Extensive simulations in the CADSL were performed in order to compare the performance in terms of error events as a function S/N ratios of the QED using various suboptimal metrics to the performance of the decoder using maximum likelihood decoding. Substantial work is in progress justifying mathematically and by continued computer simulation the use of suboptimal metrics in the TCM decoding trellis. Results to date look promising. TCM hardware implementations are:

Results to date and future projects:

1. The Hewlett Packard 64000 Development System was used to emulate a motorola MC68000 microprocessor. The emulated MC 68000 performed the metric calculations and controlled the entire decoding process such as sending the path metrics and path symbols to the trellis registers which were implemented in hardware using Altari chips. Hardware implementation showed as average bit error rate performance degradation of .75 dB for the quantized decoder. This compares favorable to the .5 dB loss observed in the CADSL computer simulations which indicates only a .25 dB implementation loss. Further, the quantized decoder demonstrated a 2-1speed increase in processing time over the unquantized decoder.
2. Work is underway to design a VLSI 8-PSK TCM QED decoder. The steps are: a) Design the Algorithmic State Machine, ASM, b) Build the processor, c) Build the controller, d) Test, e) Assemble. The ASM required for the Viterbi decoder is large and complex.

Since its design is critical, preliminary steps are in order. A computer program was designed to check the logical progression of the ASM as well as allow for changes. While the computer program allowed simulations to test its validity it is different from the CADSL simulation since it only uses blocks that are available to the ASM. The computer program validating the ASM was completed during the current grant. On the next cycle staff will complete the design of the ASM, implement the design with a board and chips, test, then perform a VLSI design and implement.

3. The design and development of logic (to handle the outboard decesion) modules that would make it feasible to use an off-the-shelf rate $1/2$ constraint length 7, 64 state binary Vertibi decoder as an 8-PSK TCM Euclidean decoder were initiated. During the next phase, staff and students will complete the design of the logic modules, implement and test using actual off-the-shelf 64-state decoders. Both chip and board and VLSI design of the logic modules will be considered.

Minimum-Shift-Keying

Components and boards which are necessary in order to implement a minimum shift keying, MSK, modulator were ordered. The purpose of this work was to gain a working knowledge of available boards such as Standford Telecom's board for generating a carrier and a quadrature carrier

and components such as double balanced mixers in order to effectively design and implement M-ary PSK systems. Further, an MSK implementation is a first step in designing a multi-h continuous phase modulation, CPM, communication system since MSK is a special case of multi-h with h (deviation ratio)=1/2. A parallel MSK modulator was implemented with the testing to be completed shortly.

Multi-H Continuous Phase Modulation

Multi-h CPM achieves spectral efficiency at the cost of system complexity by combining the modulation and coding processes. While the TCM models studied are two-dimensional and TCM demodulation may be achieved with a correlation receiver with two orthogonal basis functions (a sine-cosine quadrature detector), multi-h modulation with just two values of h is four dimensional. The signals are not orthogonal and must be orthogonalized with the Gram-Schmit process during the demodulation process prior to extracting the metric for use in trellis decoding.

The literature concerned with multi-h CPM was studied. The next step is to develop computer models for extensive simulation studies in order to determine its performance characteristics.

Communications Systems Research Overview

End-to-end system evaluation and research was a goal of the Space Telemetry and Telecommunication Systems Center. That is, a major goal was to evaluate the overall system as shown in figure 1.1. The focus of the research was on the combined demodulator and decoder, block (3) as

shown in figure 1.1. Specifically, the emphasis was on research involving the Euclidean maximum likelihood sequence decoder.

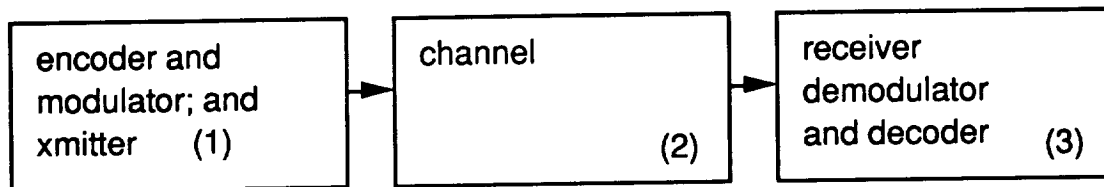


figure 1.1

Practical implementation and enhancement of the speed of the decoder using suboptimal metrics is of paramount importance in the development of TCM PSK for incorporation in a high data rate communication system; therefore the emphasis was on the decoder. Simulations and mathematical model development started at the demodulator-decoder interface as shown in figure 1.2. It was assumed that the channel, block (2) in figure 1.1, was a white Gaussian noise channel. Therefore, the I and Q components were represented by the X and Y coordinates of the TCM signal constellation plus additive Gaussian noise with a specified variance. The sequence of coordinates were generated using a TCM structure. Since the signal coordinates represent signal energy and the noise variance was specified, the probability of making an error was determined as a function of signal-to-noise ratio. Further, it was necessary to use only a quadrature detector since TCM PSK is two dimensional modulation.

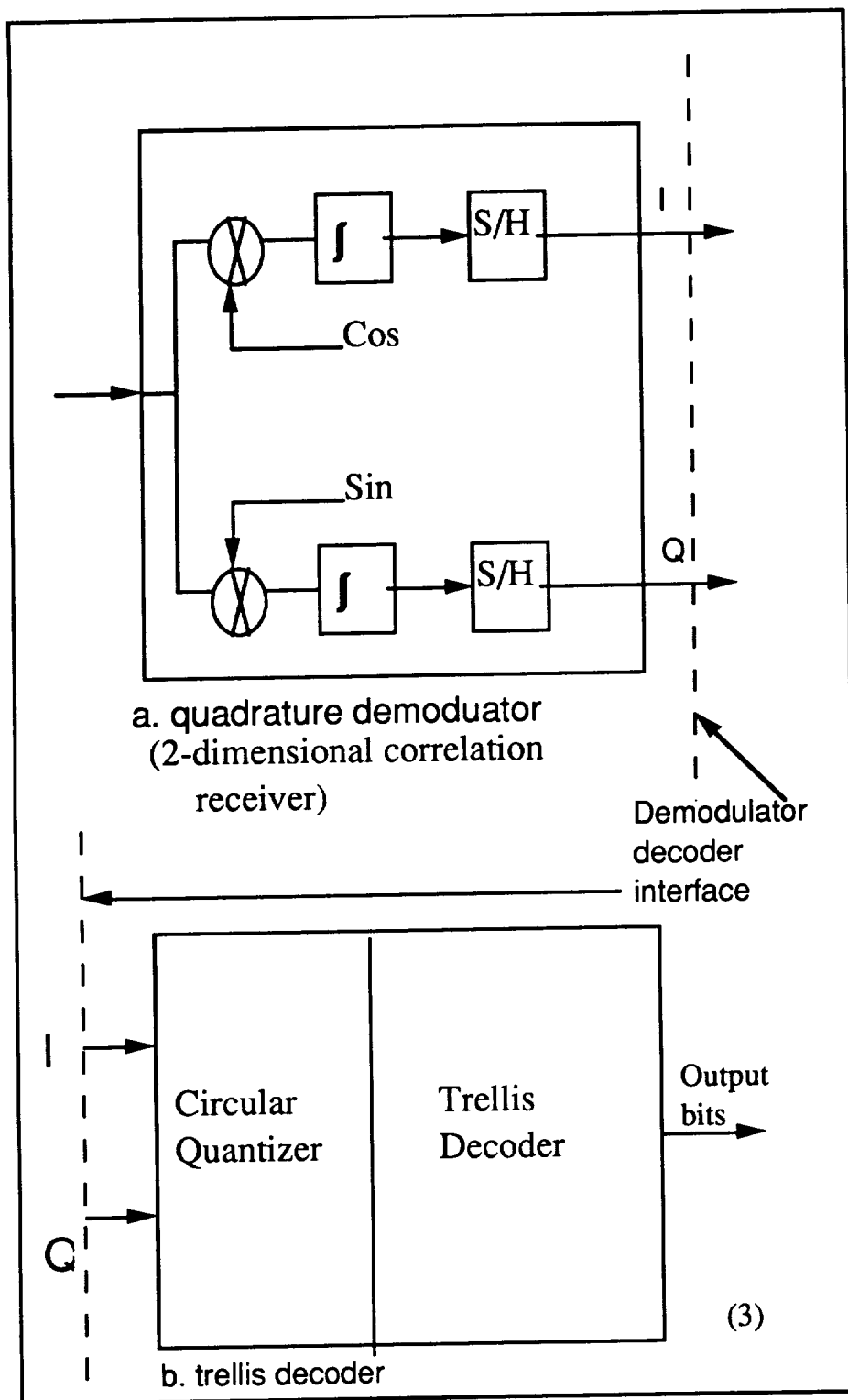


figure 1.2

Receiver, demodulator, decoder (two dimensional)

REFERENCES

- [1] Frank Carden, "A Quantized Euclidean Soft-Decision Maximum Likelihood Sequence Decoder: A Concept for Spectrally Efficient TM Systems," Proceedings of the International Telemetry Conference, Vol. XXIV, pp. 375-384, October 1988.
- [2] Frank Carden and Brian Kopp, "A Quantized Euclidean Soft Decision Maximum Likelihood Sequence Decoder for TCM," IEEE Military Communications Conference, Vol. 2, pp. 679-682, October 1988.
- [3] Frank Carden and Michael Ross, "A Spectrally Efficient Communication System Utilizing a Quantized Euclidean Decoder," Proceedings of the International Telemetry Conference, Vol. XXV, pp. 575-582, October 1989.
- [4] Frank Carden "Fast TCM: Circular Quantization and Integer Weighting" submitted for publication, Feb 15, 1990 to the IEEE Transactions on Communications. To be published.

Section 3-2

2. TELEMETRY TRANSPORT TECHNOLOGY (T³)

(Dr. Horan)

TASK 2

The Telemetry Transport Technology study deals with the packet data protocols being developed internationally for use in the Space Station Freedom. In particular, we investigated the proposed Consultative Committee for Space Data Systems (CCSDS) packet standards as part of the Advanced Telemetry Processing Pilot Program (ATP³) (See appendix I) being conducted for Goddard Space Flight Center. In this study we used commercially-developed communications simulators in conjunction with NASA mission models for the space station program to investigate the packet transport protocol, the ratio of the fill to actual data in the links, and the initial processing requirements. These studies were validated against previous studies performed for the Goddard Space Flight Center.

In the initial phase of the Center for Space Telemetry and Telecommunications Systems, we have made the following two major accomplishments in the area of Telemetry Transport Technology:

- a) the establishment of a full simulation laboratory built around a network of VAX workstations that also interface with SUN workstations and laboratory personal computers to allow for the development of simulation models of the packet transport and

- b) the replication of the performance of proprietary models developed by contractors for Goddard Space Flight Center using the commercially-available simulation tools which provide a more open access to the simulation parameters and the model configuration.

In the past year, the following presentations were made at meetings to describe the work in telemetry transport technology as sponsored here:

S. Horan , "Simulations of Space Station Data Links and Ground Processing", Proceed. International Telemetry Conference, 25, October 1989.

S. Horan, "Computer Simulations of Communication Links for Use in the Space Station System," Simulation Conference 14, San Diego, September 1989. (invited presentation).

Additionally, Dr. Horan was invited by the Tracking and Communications Division of Johnson Space Center to contribute to the telemetry and communications technology portion of the Space Transportation Avionics Technology Symposium (STATS) held in November 1989.

At the 1990 International Telemetry Conference, several papers describing work performed on the ATP³ were presented as well as Dr. Horan being a session chairman for the Space Applications session. In that session, Mr. John Watson who has been supported by this grant will describe his work in simulating the transport of space station data using the simulation laboratory facilities.

SIMULATION LABORATORY IMPROVEMENTS

Under the sponsorship of the Center for Space Telemetry and Telecommunications Systems (CSTTS), a major research laboratory has been developed in the Department of Electrical and Computer Engineering at NMSU. This laboratory has been augmented by other projects but the CSTTS has provided a capable core of equipment around which the other computers have been networked.

In the initial phase of the CSTTS, the following computer systems were acquired:

- a) VAXserver 3800 with 2.2 GB of disk and 16 MB of memory,
- b) two VAXstation 3100 with local disks and 8 MB of memory,
- c) VAXstation 3100 with 200 MB of disk and 16 MB of memory,
- d) VMS operating system, FORTRAN and C languages, various utilities, and
- e) DECnet and TCP/IP local area network support.

The CSTTS simulation facilities also supported the acquisition of the software packages Block-Oriented Systems Simulator and Signal Processing Worksystem, both from COMDISCO, for the analysis work. This software is augmented by other products acquired by related projects.

One trend that the software vendors have made known to the CSTTS is the possibility that many of the simulation products will not carry continued support under the VMS operating system that we currently use and will begin migrating those products to a UNIX-based configuration.

LASER COMMUNICATIONS

Research in the laser communications area places emphasis on novel technology for free-space laser communications systems. There are currently 4 MS candidates working in this area. Diode laser based Free-Space Laser Communications offers the promise of very high data rates (tens of GHz) with a lightweight, low power consumption and if desired a highly directional system.

An important issue for any free-space laser communications systems is solar background noise rejection. The conventional approach has been to use a coherent communications systems to provide high noise rejection or a direct detection system whose transmitter power is high enough to overwhelm the noise. As a result of the poor noise rejection the simple reliable direct detection systems have, until now offered inferior performance when compared to the more complex coherent detection systems. While the coherent detection diode laser systems offer superior performance, they have a number of serious drawbacks that have so far confined the coherent system operation to the laboratory environment. This is, in large part due to the difficulty in obtaining matched local oscillator and transmitter lasers and in the complexity of tracking the frequency changes in the transmitter laser. As a result of these practical problems associated with the coherent detections systems and in light of a recent advance in ultra-high noise rejection optical filters for direct detection (i.e The Faraday Anomalous Dispersion Optical Filter (FADOF) invented by Dr. T.M. Shay June 1988) we decided to pursue the investigation of direct detection communication systems. The FADOFs provide a factor of 2000 higher optical noise rejection than interference filters and hence offer between 50 and 60 dB solar noise rejection and 50 dB channel isolation. When a FADOF is used in a

direct detection communication system the performance should be similar to the coherent detection system. Therefore, we chose to explore the use of a FADOF receiver in free-space laser communications.

Our progress to date has consisted of, i) ordering equipment necessary for our laser communications experiments, ii) setting up our dye laser tuneable test oscillator system, iii) constructing high precision diode laser controllers (design donated to Laser Communications Laboratory by Limerick Corp. solely for university use), iv) 3 journal articles, one to be published in the June 1990 IEEE Journal of Quantum Electronics, one article published in July 1990 Optics Communications based upon this work and have submitted other manuscripts to Optics Letters and Applied Physics Letters, iv) Demonstrated a novel, simple and robust method for frequency locking diode lasers to a remote narrow band receiver, v) demonstrated the FADOF concept, and vi) presented 9 conference papers.

The FADOF is an optical filter based entirely on the resonant Faraday Effect. The filter system consists of two crossed polarizers and vapor cells. If the applied magnetic field, the vapor density and the cell length are all properly adjusted then a narrow band of frequencies have their polarization rotated by 90° and hence are transmitted through the filter, while all other frequencies are not rotated and hence extinguished by the second polarizer. We have experimentally demonstrated this for the first time and have measured a transmission of 63%, a bandwidth of 1 GHz to 10 GHz (the 10 GHz figure demonstrated at an industrial laboratory) and out of band noise rejection of 50 dB. The filter transmission frequency depends only weakly on the applied magnetic field and the vapor density and hence can

be set with nearly absolute precision. This is a high sensitivity imaging direct detection device that also has wide field-of-view for ease in signal acquisitions.

Papers

1. "Ultra-High Resolution, Cs Laser-Excited Optical Filter for Doubled Nd Lasers" T.M. Shay, Optics Communications. 77, 368, 15, July 1990.
2. "Theoretical Model for a Background Noise Limited Rb Laser-Excited Optical Filter for Doubled Nd Lasers," T.M. Shay and Daniel F. Garcia, IEEE Journal of Quantum Electronics, QE-26, 1135, June 1990.
3. "400 Hz Frequency Stability of a GaAl As Laser Frequency locked to the Rb (D2) Line" Y.C. Chung and T.M. Shay, 29 681, June 1990.

Conferences

1. International Conference on Lasers 1989, New Orleans, LA, December 4-8, 1989. "Laser-Excited Optical Filters." T.M. Shay.
2. International Conference on Lasers, New Orleans, LA, December 4-8, 1989. "Theoretical Model for a Faraday Anomalous Dispersion Optical Filter." T.M. Shay and Daniel F. Garcia
3. International Conference on Lasers, New Orleans, LA, December 4-9, 1989. "A Simple Ultra-High Resolution Optical Receiver: Theory for the Rb (D2) Transition," T.M. Shay and David Dick.

4. International Conference on Lasers, New Orleans, LA, December 4-8, 1989. "A Simple Ultra-High Resolution Optical Receiver: Experiments in Rb Vapor", David Dick and T.M. Shay.

Invited Presentations

1. "Ultra-High Noise Rejection Optical Filters.", Chemistry and Laser Science Division, Los Alamos National Laboratory, January 10, 1990.
2. "Optical Receivers for Submarine Laser Communications", Vanderbilt University, Nashville, TN, Dec. 12, 1989.
3. "International Conference on Lasers 1989, New Orleans, LA, December 4-8, 1989. "Laser-Excited Optical Filters."

Astronomy (Dr. Rita Beebe)

Image Processing and Interpretation

The current status of the Hubble Space Telescope (HST) has given impetus to increasing our involvement in image deconvolution. The focus problems of optical train assembly of the telescope appear to be due to spherical aberration, with the focus of central rays falling in front of off-axis rays. These problems lead to a best focus where 15% of the light falls into a sharp spike with a diameter less than 0.2 arc seconds. The remaining light is spread in a disk around the central spike and spans more than an arc second. The original specifications for the telescope required that 85% of the light fall within an 0.2 arc sec disk. Therefore, until the planned replacement for wide field/ planetary camera can be installed, we are faced with smeared images and with the choice of lengthening exposures or widening the slit of the ultra-violet spectrographs. Although this will lead to downgraded performance, the fact remains that these instruments have unique UV capabilities that cannot be realized with ground-based telescopes.

Because the smearing function should not vary with time and should be characteristic of the optical assembly, it can be characterized by careful analysis of star fields that will serve as arrays of point sources. There will be considerable effort expended to deconvolve the effective slit from the spectroscopic data as well as to improve the UV images. The techniques that are required are those of standard image processing and as such should be a part of every investigators toolkit. Therefore, it is logical that we look at this problem in the general context of improving the resolution of optical data.

For the last two years we have operated a CCD camera at the 60 cm. planetary telescope at Tortugas Mountain. The signal-to-noise ratio in these images is high enough that we have gained a factor of 2 or more in spatial resolution by using a constrained deconvolution technique. The smearing function for these images is dominated by random motion in the earth's atmosphere and is represented as a Gaussian, specified by an estimated half-width. These images are sampled at 0.25 arc second and the Gaussian half-width is typically a half arc second. Preliminary investigation indicates that the Hubble Space Telescope smearing function can be represented as the sum of a sharp central Gaussian and a more slowly varying radial function that represents the outer disk. The degree to which these images can be improved will not be markedly better than our best groundbased images; however, the smearing will be more consistent than in the ground-based data and the UV images will be unique. UV, narrow-band red images in regions where methane gas absorbs effectively and broadband orange images will be compared to optimize the data.

At the same time we have developed the ability to rapidly digitize the archival photographic images with a solid state camera that is interfaced with a PCIP image board in an IBM-AT type computer. When observing conditions were ideal, these images were obtained within seconds of each other. We will co-add digitized images to reduce the random noise that is introduced by the variation in grain size in the emulsion. The number of images that can be added will be determined by the rotation rate of Jupiter (36 degrees/per hour) which will smear the images in an east-west direction. This consistent data set spans more than 25 years and is directly available to our students.

